

Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring
ASP Conference Series, Vol. TBD, 2000
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Modeling Observational Signatures of Disk-Driven Outflows

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Abstract. We present a self-consistent, semi-analytical dynamical model of disk driven outflows in AGNs that are accelerated by a combination of magnetic stresses and radiation pressure. This model will make it possible to examine scenarios in which the wind is homogeneous as well as cases where it consists of dense clouds embedded in a more tenuous, magnetized medium. The various ingredients of this model will be tested through quantitative predictions from both multiwavelength spectral observations and reverberation mapping of AGNs.

1. Introduction

Many researchers have theorized about the structure and dynamics of the gas near the cores of AGNs, specifically in the Broad Emission Line Region (BELR), Broad Absorption Line Region (BALR), and the Warm Absorber (WA). In addition, there are open questions as to how all of these different regions might be related, if at all.

In attacking these questions, different investigators have invoked various processes and physical effects to explain observations of AGNs. Researchers have hypothesized that the gas may exist either as discrete clouds or as continuous winds. The idea that the gas is partitioned into discrete clouds is the more “traditional” approach to BELR modeling (Bottorff et al. 1997). However, recent spectral analysis by Arav et al. (1997, 1998) seem to show that a continuous wind might be better suited to explain high resolution spectra of broad lines.

Second, to explain the acceleration of the gas to the velocities observed in spectral lines, various researchers have suggested either radiative acceleration or magneto-centrifugal acceleration. Radiative acceleration from a central continuum source was proposed by Arav, Li, & Begelman (1994) and Arav (1996) to explain the acceleration of gas in the BALR. Later, Proga (2000) examined radiative acceleration due to continuum emitted by a circumnuclear accretion disk as well as the central source. Other researchers have invoked magneto-centrifugal acceleration (Königl & Kartje, 1994), which appears to explain the central dusty torus through the natural vertical density stratification in the magneto-centrifugal wind.

Of course, investigators don’t usually include just one of the above possibilities; many different combinations of mechanisms have been attempted. Em-

mering, Blandford, & Shlosman (1992) modeled the cores of AGNs by using a magneto-centrifugally driven continuous outflow to simulate discrete clouds. This model was later improved (Bottorff et al. 1997) to explain line variabilities.

Working with radiative acceleration only, Murray et al. (1995) and later Chiang & Murray (1996) modeled the gas as a continuous wind, driven by continuum and line radiation forces from both the central source and the disk. They used the inner edge of the wind as a shield and therefore as a possible origin of the Warm Absorber, and also explained the Broad Emission Line (BEL) profiles with the wind itself.

Finally, de Kool & Begelman (1995) used a continuous wind with magneto-centrifugal driving and continuum radiation pressure to examine the effects of radiation pressure on the magnetic outflow structure. Also, Königl et al. (1995) and Kartje et al. (1997) explained EUV absorption features in BL Lac objects using both magnetic and radiative acceleration. They accomplish this by first lifting material vertically away from the disk using magneto-centrifugal driving (modified by including an approximate radiation pressure in the self-similar wind equations). The material travels upward along the magnetic streamlines until it intercepts the central beaming cone of the BL Lac, where the gas is forced out radially by both line and continuum radiation pressure. The clouds move radially outward, absorbing the central continuum at a range of velocities as they accelerate, yielding broad absorption troughs in BL Lac spectra.

2. Open Questions

As one might imagine, there are still a few open questions to consider about many of these models.

Specifically, concentrating on the Murray et al. model, we need to understand how well the radiative acceleration actually works for a continuous wind as postulated on the scales and parameters in this model. In their paper, they cite approximate calculations to show that it may be feasible, but no explicit model for the shielding column is presented, although it is theorized that the shield is a “failed wind” region driven by disk radiation pressure that falls back to the disk. The difficulty is that the radiative acceleration being proposed has never been simulated for the continuous wind hypothesized in these models. We point out that even though it has been hypothesized that radiative acceleration from the disk continuum could push material up into a wind (Proga 2000), a magneto-centrifugal wind can also accomplish that, and can already explain the observed obscuration near the disk. In addition, as pointed out by Kartje et al. (1997), such winds could be important for lifting material into the beaming cone of BL Lacs. Also, in BALQSO objects, magneto-centrifugal winds could explain the more equatorial flow pattern if the magnetic streamlines are pushed by radiation pressure from being nearly vertical to being more radial or equatorial. The winds could then be the source of both the BL Lac and BALQSO absorption features. These options are displayed in Figures 1 and 2, where we present a possibly geometry for BL Lac and BALQSOs with a magneto-centrifugal wind and clouds.

There are open questions left by the Königl & Kartje work as well. First, how well can a “clumpy” medium explain both BL Lacs and BALQSOs, as

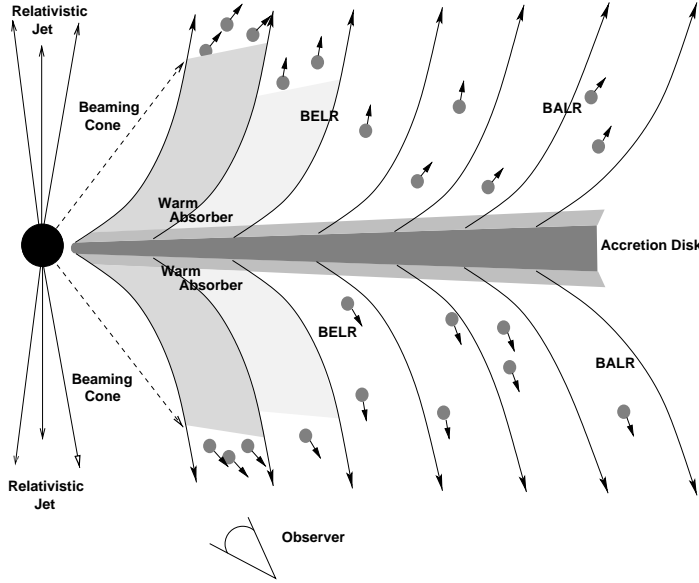


Figure 1. Schematic Geometry for a BL Lac with a magneto-centrifugal wind and clouds. The curved lines up from the disk represent magnetic field lines. The shielding column required for radiative acceleration exists in the darker shaded regions above the accretion disk as well as at the innermost portion of the wind. In this class of AGN, the magneto-centrifugal wind lifts the clouds out of the plane of the accretion disk, where they intercept the central continuum and are radiatively accelerated.

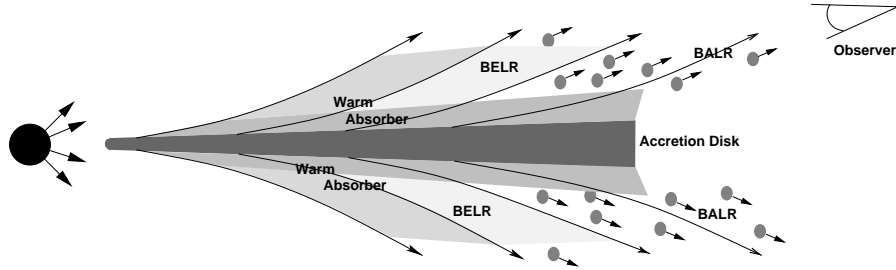


Figure 2. Possible Geometry for a BALQSO with a magneto-centrifugal wind and clouds. As in the BL Lac figure, the shielding column required for radiative acceleration exists in the darker shaded regions above the accretion disk as well as at the innermost portion of the wind. In BALQSOs, the magnetic field lines are pushed away radially by the radiation pressure from the central source on the clouds in the wind, resulting in a much more equatorial wind.

postulated above? Second, are the BELR, BALR, and WA regions present in their wind, or is it not possible to explain all of these observed features with one model of this type? The magneto-centrifugal wind model accounts for the density stratification near the disk, the uplifting of gas into the BL Lac beaming cone, and would naturally produce the gas shield required in the Murray et al. (1995) theory for radiative acceleration to operate. Can this wind then also produce a BELR within its inner region, perhaps? Does the outer region of the wind contain gas like that observed in the BALR?

Third, and more generally, while the Königl & Kartje work postulates a “clumpy” medium, can a continuous medium explain the observations without magnetic fields? Is it possible that radiation pressure from the disk could launch a continuous wind? In this case, radiation pressure would substitute for magnetic field acceleration near the disk, and whereas magnetic fields are usually invoked to confine clouds, with a continuous wind such confinement would not be needed. Also, while variability observations would seem to fit the picture of a clumpy medium, Arav et al. (1999) suggest that even a continuous medium could produce variability due to instabilities in line-driven continuous winds. Therefore, we ask, how can we test observationally for a “clumpy” medium, and indeed, is a clumpy medium required? Can we constrain the gas to be clumpy or continuous based on observations?

We need a model to compare to the observations, both for the effects of a clumpy or continuous medium and to compare radiative acceleration vs. magnetic effects. We are developing such a model, and will use that model to generate predictions that will constrain the physics at the cores of AGNs.

3. Proposed Hybrid Model

In pursuit of answers to the above questions, we are developing a quantitative, semi-analytical method that includes many of the above effects to enable comparisons with observations for multiple types of AGNs within a self-consistent model. We include:

- a self-similar model of the magnetohydrodynamic wind,
- radiation pressure from the central source,
- the two-phase nature of the gas (clouds within a continuous gas medium), including the coupling of the two phases, and
- the effects of disk continuum (intrinsic and reprocessed) as a source of radiative acceleration.

We’ve chosen to start with these main ingredients because it seems that we need magnetohydrodynamic, centrifugally driven winds and radiation pressure to explain BL Lacs and perhaps BALQSOs, and continuous winds have had other successes explaining broad emission lines and reverberations results. Therefore, we will combine them to see what they produce when united, and what constraints their “dual” presence requires.

In our progress so far, we have worked on implementing the first two elements together. We have developed a self-similar model of the magnetohydrodynamic wind like that of Königl & Kartje (1994), except for an improved treatment of the radiative term, $\Gamma(\theta)$ ($\Gamma(\theta) = a_R/g$, the ratio of the radial radiative acceleration to the gravitational acceleration) in the original equations. This first program determines the shape of the field lines from solving the cross-field (Grad-Shafranov) equation in a self-similar formulation. Next, we use the wind structure output from that self-similar program as input to the photoionization code Cloudy to determine the ionization state of the gas given the self-similar scaling of the density. The ionization output from Cloudy is then used to more accurately compute the line and continuum force multipliers that determine the radiative acceleration a_R :

$$a_R = \frac{n_e \sigma_T F}{\rho c} [M_{line}(\Xi, t) + M_{cont}(\Xi)], \quad (1)$$

where n_e is the electron density, σ_T is the Thomson scattering cross section, F is the total incident radiation flux, and ρ is the density of the medium undergoing radiative acceleration. M_{line} and M_{cont} are the line and continuum force multipliers, representing the ratio of line and continuum acceleration to that of Thomson scattering alone. The line force multiplier is a function of t , the “equivalent electron optical depth scale” (Arav, Li, & Begelman 1994), related to the thermal speed in the gas, v_{th} , ϵ and the velocity gradient through $t = \sigma_T \epsilon n_e v_{th} / (dv/dr)$, where ϵ is a factor to reduce the optical depth due to the small filling fraction of the absorbing matter. Both force multipliers are functions of the ionization state of the gas, Ξ :

$$\Xi = \frac{F_{ion}}{n_H k T c}, \quad (2)$$

where F_{ion} is the hydrogen ionizing flux in the incident continuum and n_H is the density of hydrogen in the gas.

Returning to our numerical model, Cloudy determines the ionization state of the gas necessary to calculate these expressions accurately. We then integrate Euler’s equation, calculating the poloidal motion along the magnetic field lines fixed by the self-similar code, but using the improved estimates of a_R from the Cloudy simulations. This allows a new determination of the velocity, density, and radiation pressure along the flow line which is then input back into our first self-similar program. We repeat the process, iterating towards convergence of the effects of both magnetic and radiation forces. In both of these steps, we take the clouds to be confined by the wind’s (mostly magnetic) pressure, as suggested by earlier authors. Our work will advance the inter-relation between clouds and the magnetic fields as we will consider the force of the clouds (when radiatively accelerated) on the magnetic field structure, as well.

When the first two elements of the model have been completed and tested, we will proceed to the third element of our model (the two-phase nature of the gas), which has not been considered by previous researchers. We will include the effects of ram pressure of the continuous wind on the clouds, and examine what effect that pressure has observationally and what impact those forces have on launching of clouds as well as their later dynamics. The fourth part of our model

(including radiation pressure from the disk continuum) has been considered by Proga (2000). We will compare this effect to the already simulated magnetic effects to assess the relative importance of the different ingredients and make observable predictions for each.

Overall, we wish to build a model capable of producing predictions of how all of the above components relate. Matching the model with observations will allow us to see which of the different components work in the quantitative models: are any of the elements absolutely required or are there perhaps included effects that don't fit with the observations?

This model, however, should not be taken as a unification scheme or as a single model that aims to explain all AGN phenomena. Our present goal is instead to check the different physical effects that have been invoked by different researchers and compare them with AGN observations to constrain the key processes active in different kinds of AGNs.

4. Observational Possibilities

There are many questions which the above theoretical/numerical framework would address. Below, we consider a few of the important ones we will concentrate on.

First, this framework will show how a two-phase gaseous medium would affect the MHD wind flow, and should allow us to explore how those effects would be visible in observations of AGNs, particularly in transfer functions from reverberation mapping. If a two-phase medium exists in the cores of AGNs, we might expect to see gas with different ionization parameters in similar sections of the wind, hence sharing the same kinematic signature. This model will predict the effect of those different ionization states on the transfer function used in reverberation mapping.

Also, this model should be able to show what differentiates the BELR, BALR, and WA in the context of all of the included physical effects. If we analyze incoming observations against this more inclusive model, perhaps we can start to relate the various components: how do their densities, velocities, and origins compare, for instance?

We also ask how dynamical effects within the wind will affect AGN spectra. Perhaps we can explain some of the observed variability by outbursts in this kind of radiatively driven, magneto-centrifugal wind?

Finally, we will predict spectral lines that might be observable by *Chandra* or *XMM*. The model will also calculate continuum and line polarization from each model to test for the presence of different dynamics in different AGN. Kartje (1995) has already studied continuum polarization effects, and this model will allow us to advance that work and examine line polarization effects as well.

Acknowledgments. We acknowledge the support of NASA grant NAG5-9063. Also, we thank Rita Sambruna for her guidance in BL Lac modeling during the summer of 1999.

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